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(54) **ULTRASONIC SURGICAL DEVICE AND METHOD FOR DETECTION OF ATTACHMENT OF ULTRASONIC PROBE**

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A61B 17/32	(2006.01)
A61B 18/00	(2006.01)
A61B 17/00	(2006.01)
A61B 90/00	(2016.01)

(52) **U.S. Cl.**

CPC ***A61B 17/320092*** (2013.01); *A61B 2017/0003* (2013.01); *A61B 2017/00017* (2013.01); *A61B 2017/00477* (2013.01); *A61B 2017/320094* (2017.08); *A61B 2018/00607* (2013.01); *A61B 2090/0808* (2016.02); *A61B 2090/0812* (2016.02); *A61B 2560/0276* (2013.01)

(58) **Field of Classification Search**

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USPC 702/56
See application file for complete search history.

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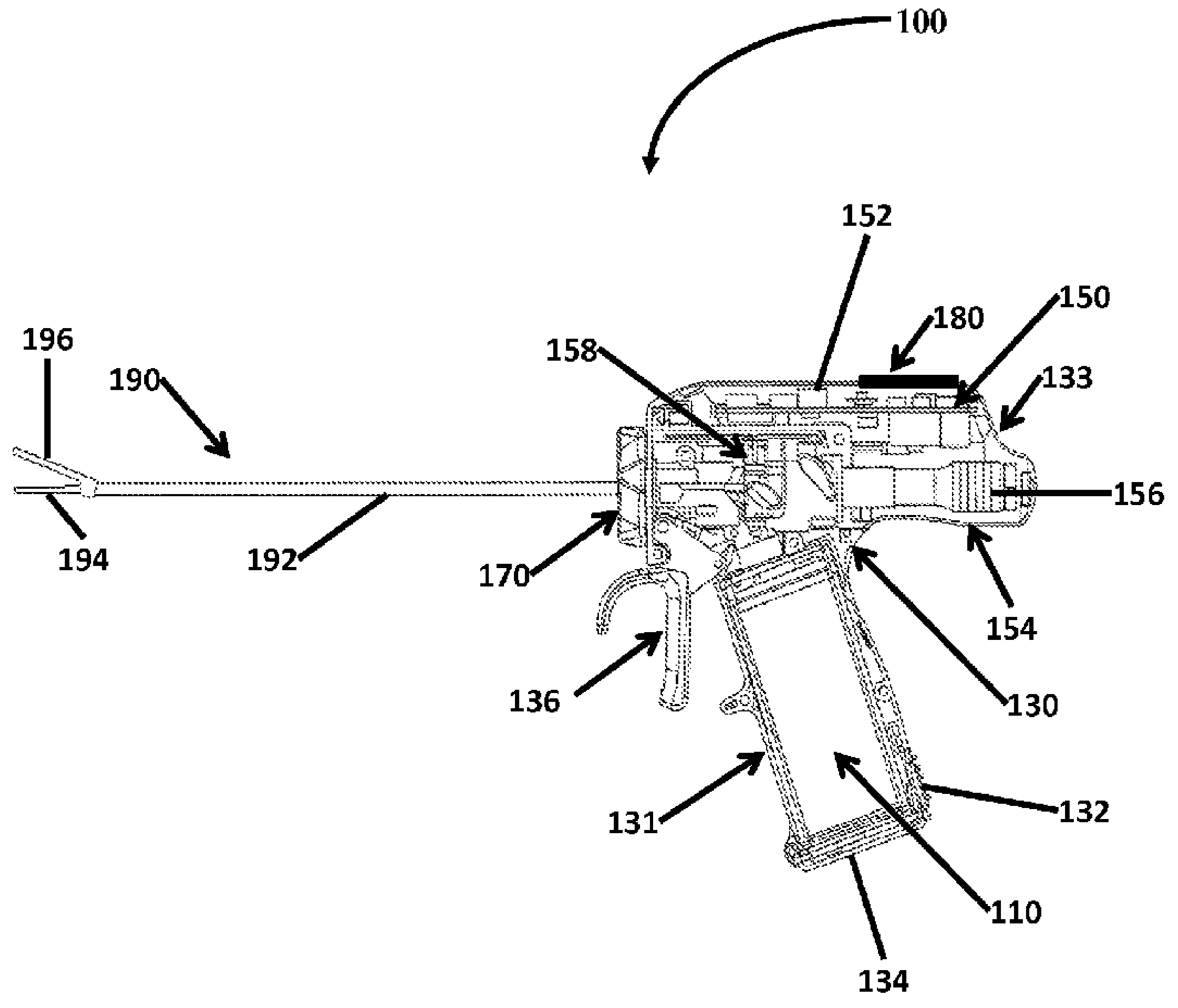
Primary Examiner — Hoai V Ho

(57) **ABSTRACT**

An ultrasonic surgical device includes a power source configured to generate power, an ultrasonic transducer electrically coupled to the power source and generating ultrasonic motion in response to the generated power, a sensor sensing current of the generated power supplied to the ultrasonic transducer, an ultrasonic probe mechanically couplable to the ultrasonic transducer, and a controller that receive a sensed current from the sensor, performs a frequency response analysis based on the sensed current, calculates a first resonant frequency and a first anti-resonant frequency of the transducer prior to coupling the ultrasonic probe based on the frequency response analysis, calculates a second resonant and second anti-resonant frequencies of the transducer based on the frequency response analysis prior to determining coupling to the ultrasonic transducer, and determines whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second resonant and anti-resonant frequencies.

19 Claims, 8 Drawing Sheets



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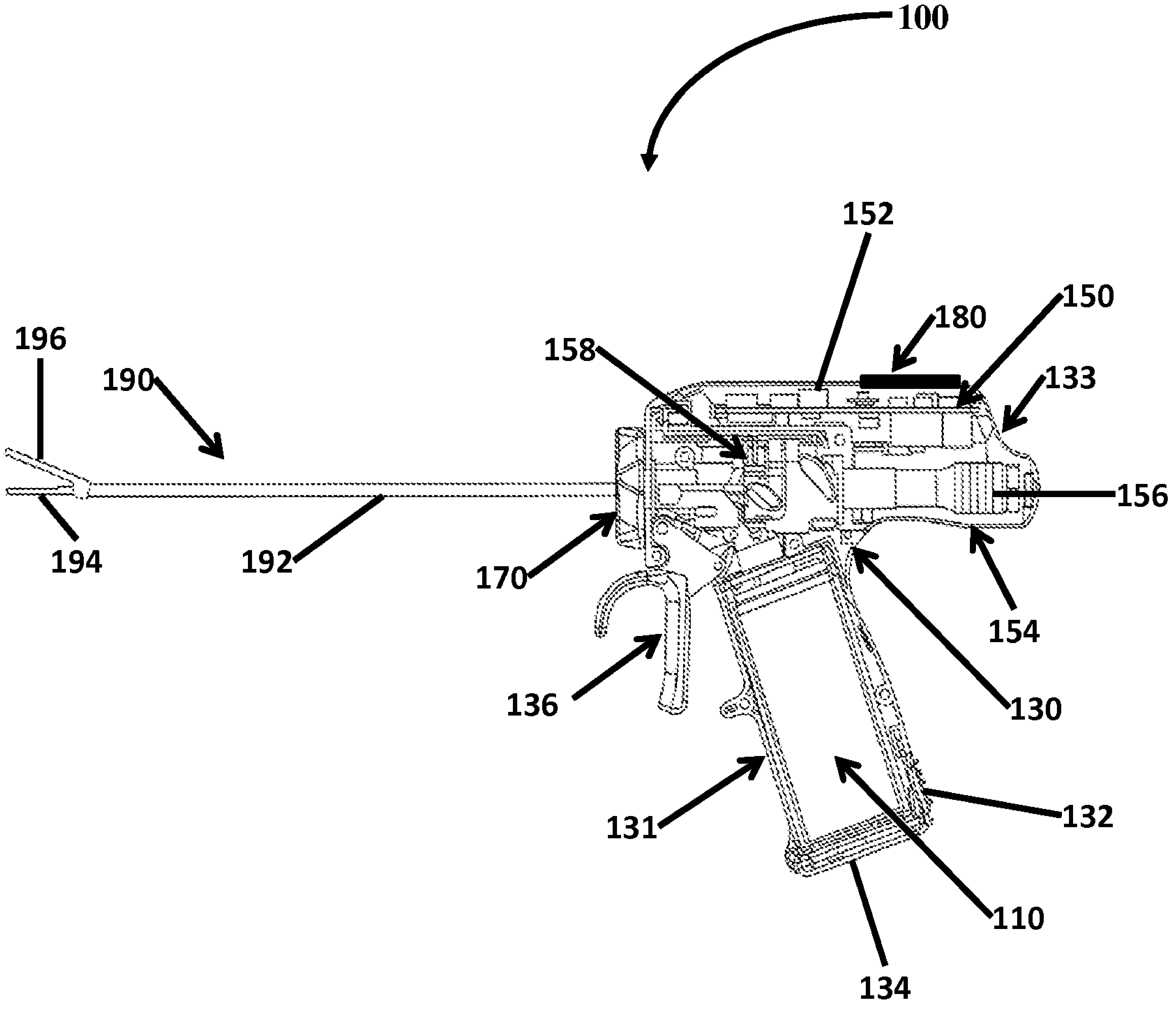
100
152
180
150
133
196
190
158
156
194
192
170
154
136
130
131
132
110
134

FIG. 1A

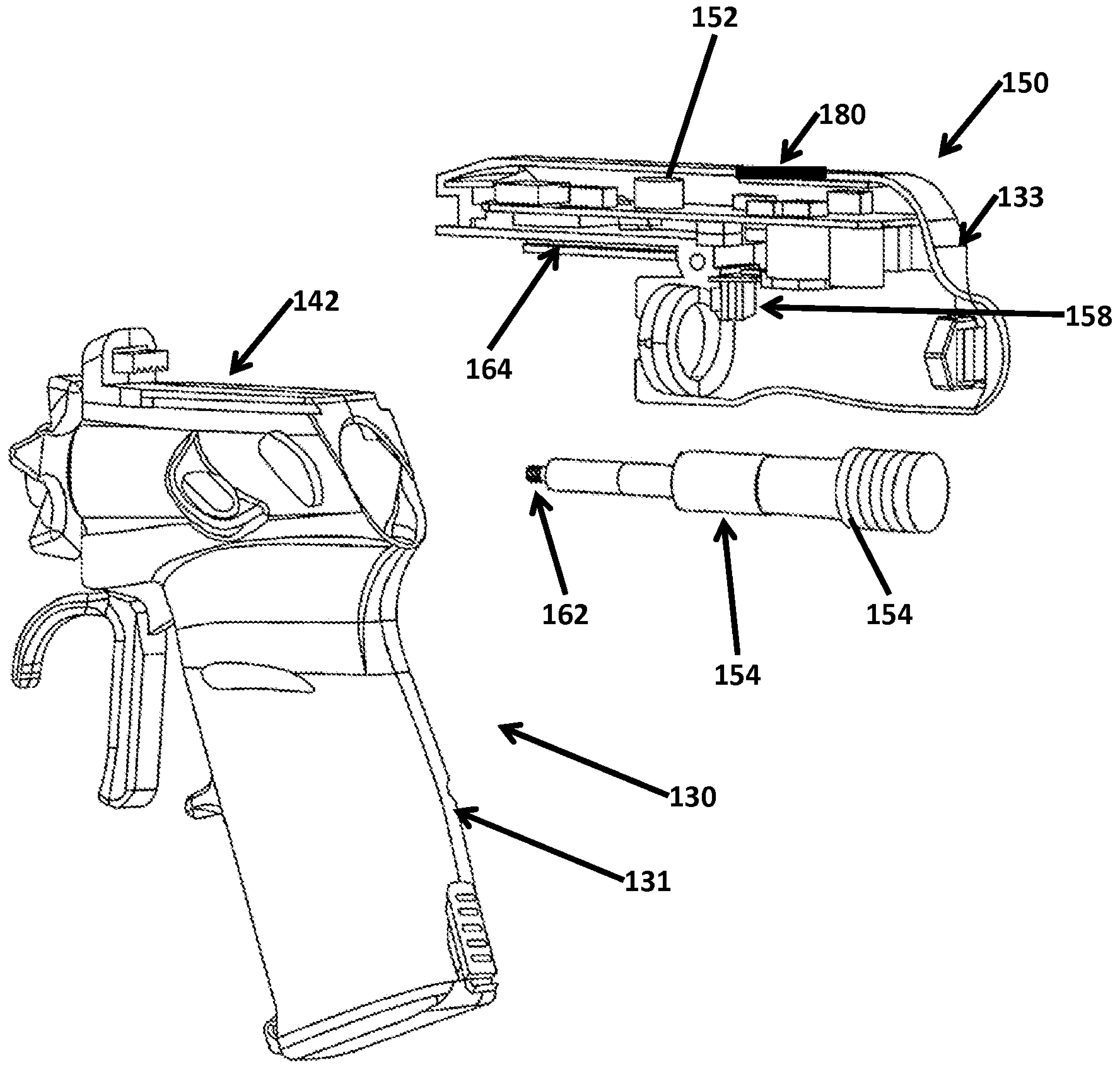

FIG. 1B

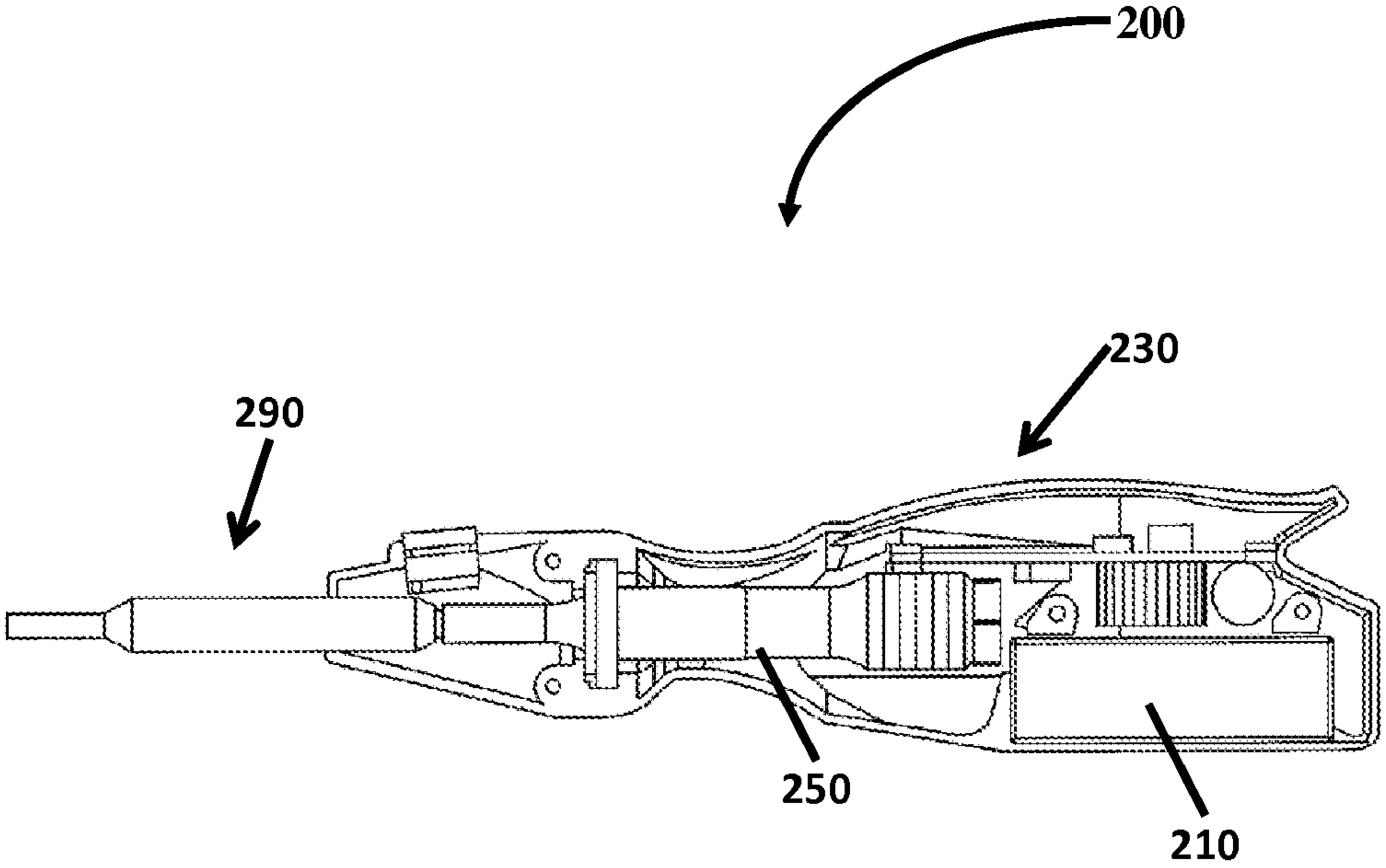

FIG. 2

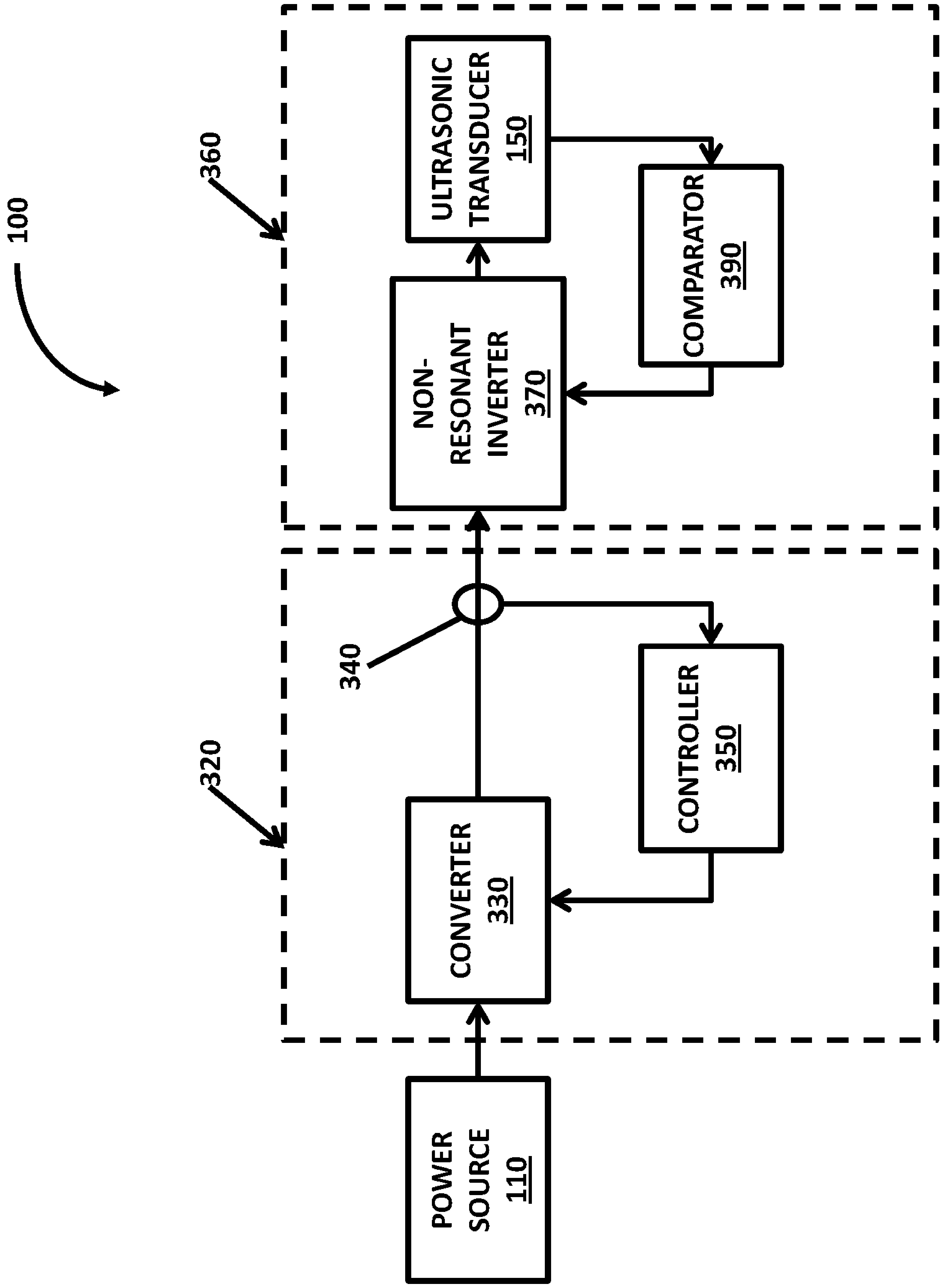
100
360
320
340
ULTRASONIC TRANSDUCER 150
NON-RESONANT INVERTER 370
COMPARATOR 390
CONVERTER 330
CONTROLLER 350
POWER SOURCE 110

FIG. 3

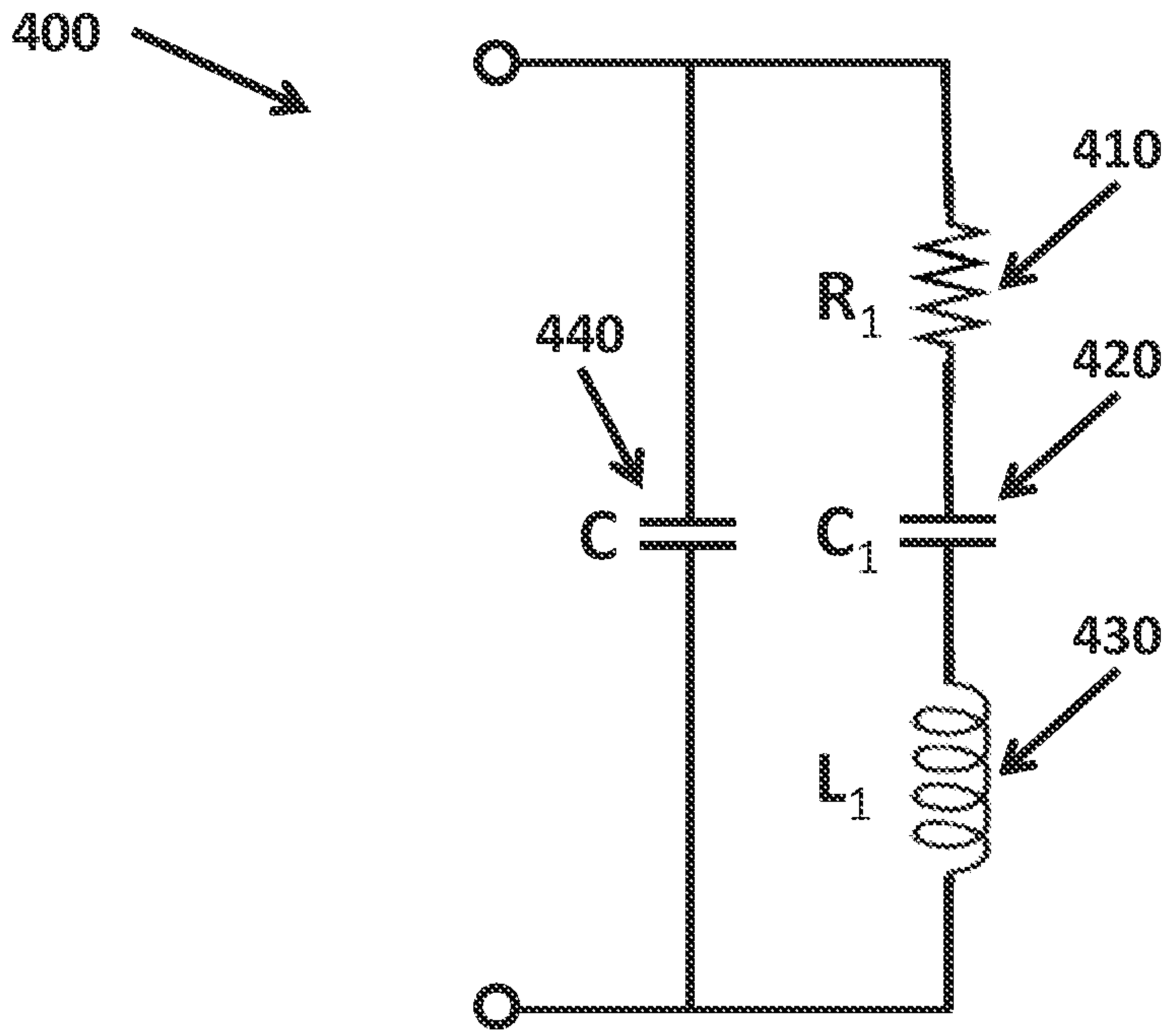

FIG. 4

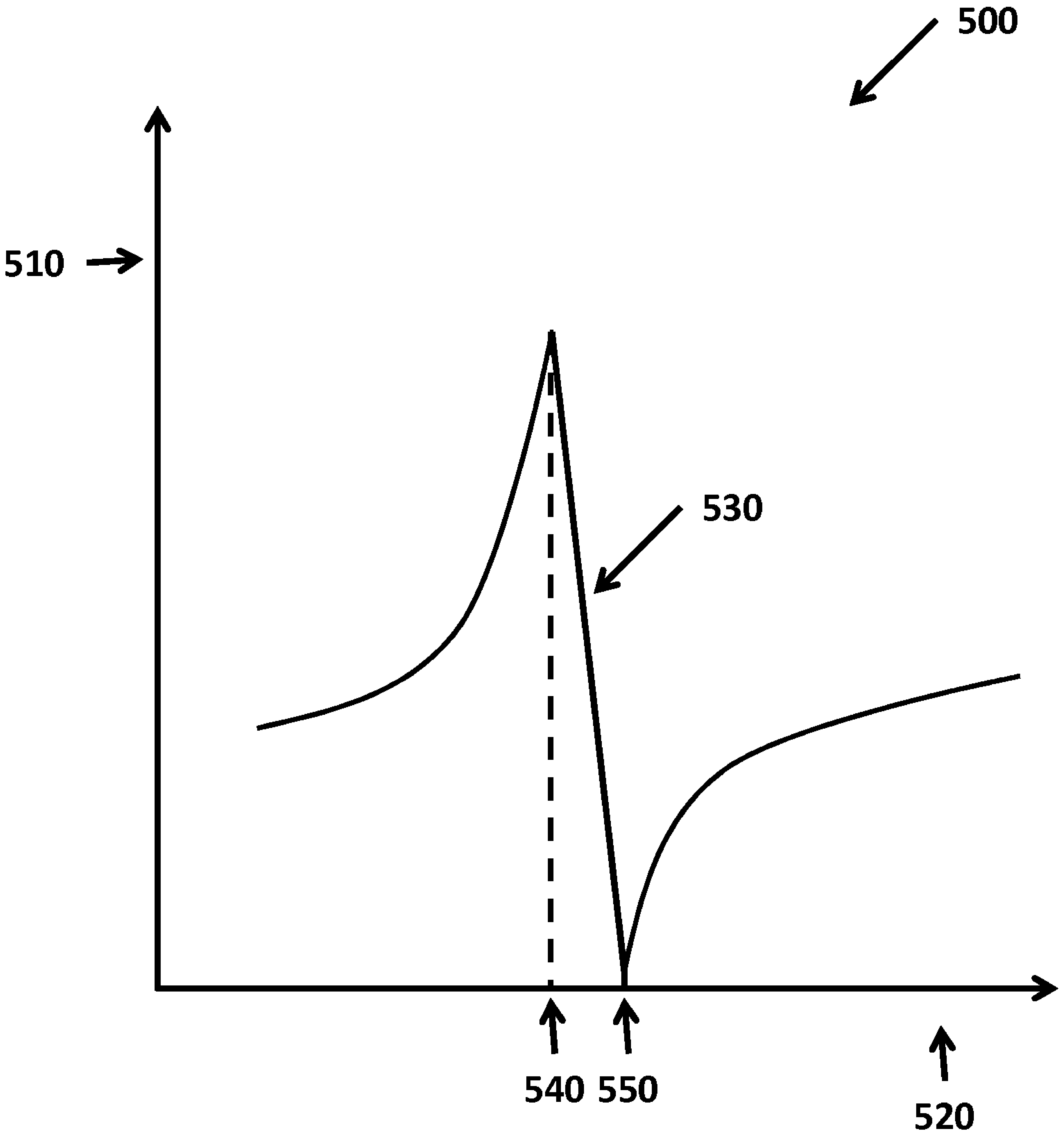

FIG. 5

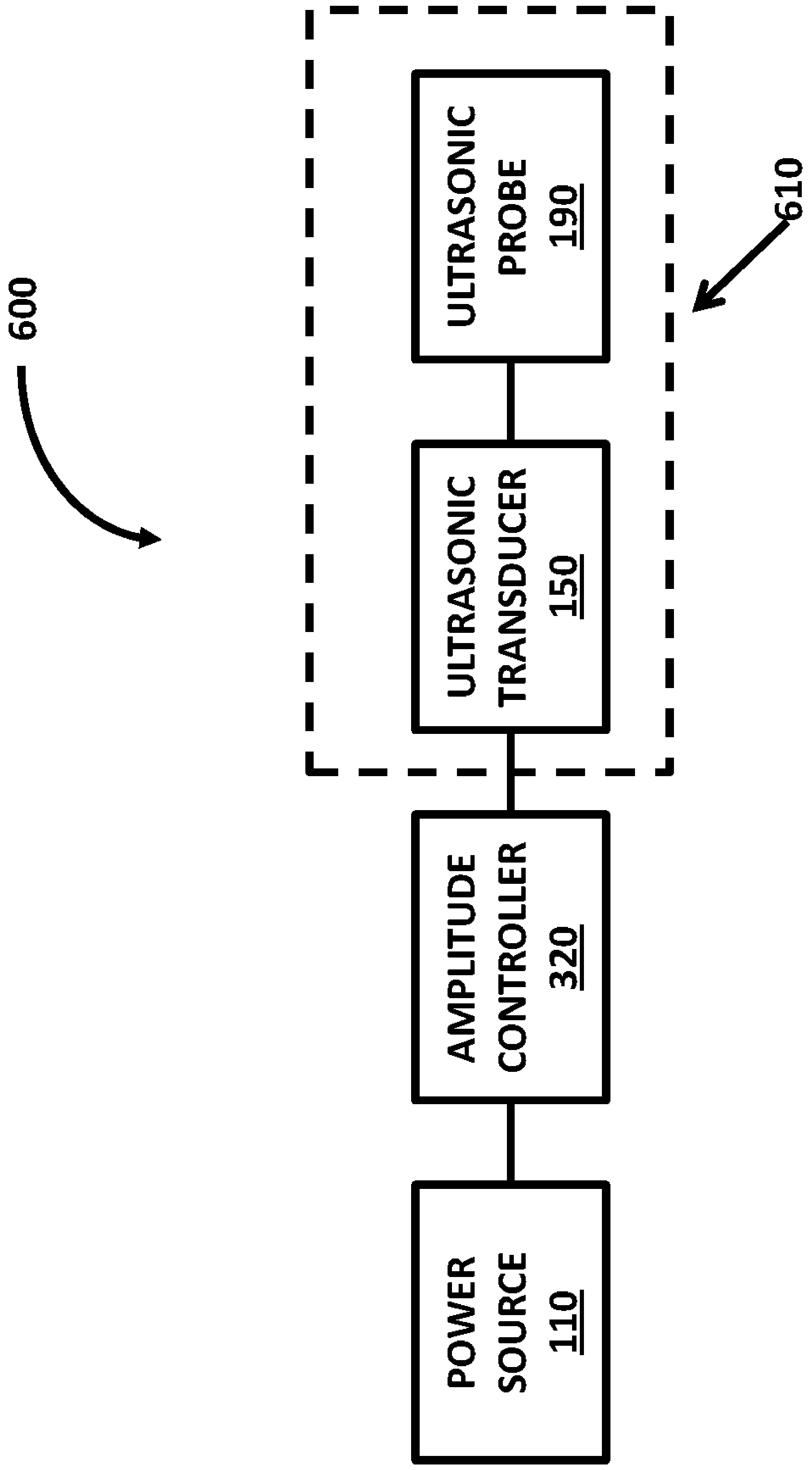
600
610
ULTRASONIC PROBE 190
ULTRASONIC TRANSDUCER 150
AMPLITUDE CONTROLLER 320
POWER SOURCE 110

FIG. 6

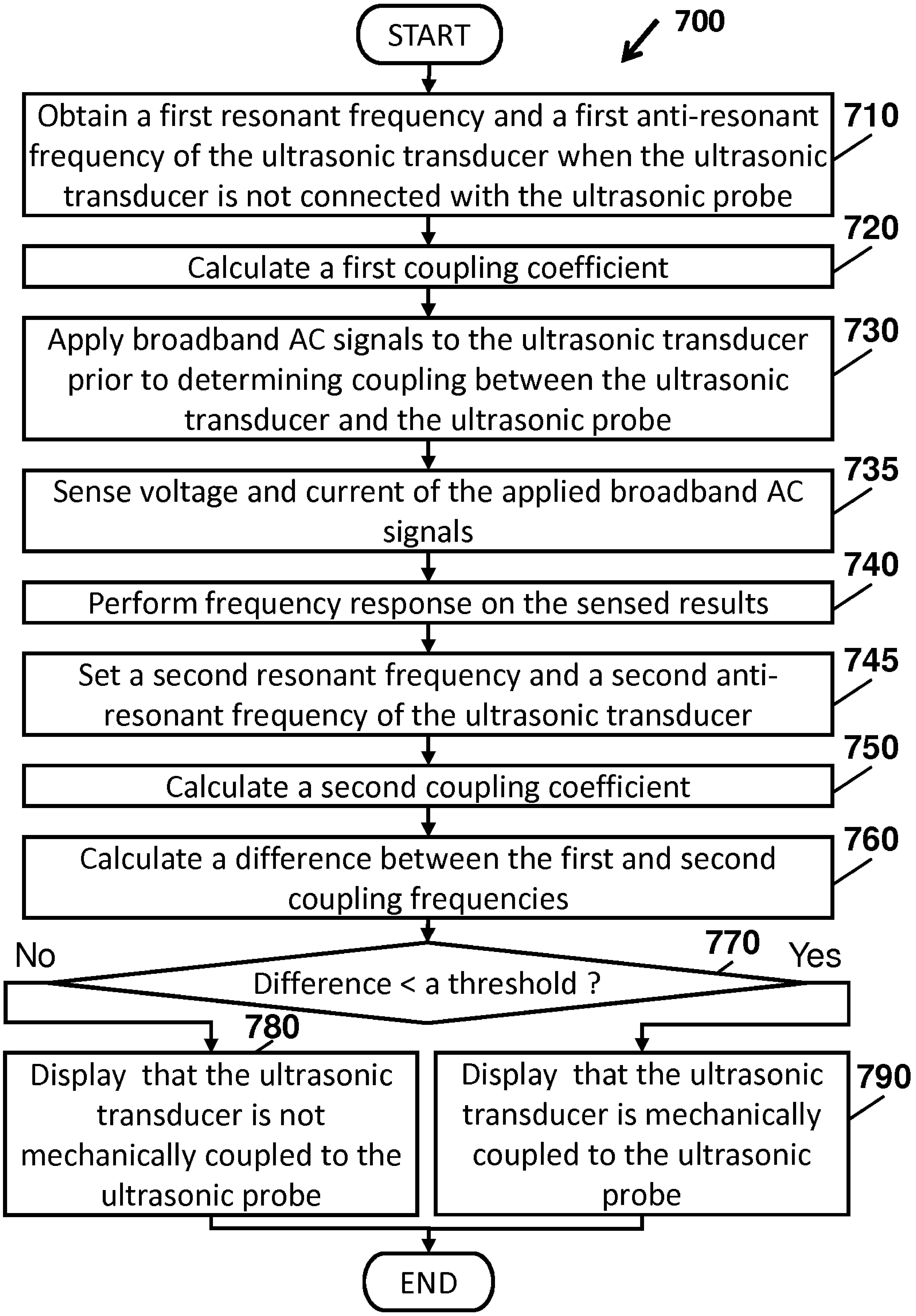
START
700
Obtain a first resonant frequency and a first anti-resonant frequency of the ultrasonic transducer when the ultrasonic transducer is not connected with the ultrasonic probe
710
Calculate a first coupling coefficient
720
Apply broadband AC signals to the ultrasonic transducer prior to determining coupling between the ultrasonic transducer and the ultrasonic probe
730
Sense voltage and current of the applied broadband AC signals
735
Perform frequency response on the sensed results
740
Set a second resonant frequency and a second anti-resonant frequency of the ultrasonic transducer
745
Calculate a second coupling coefficient
750
Calculate a difference between the first and second coupling frequencies
760
No
Difference < a threshold ?
770
Yes
780
Display that the ultrasonic transducer is not mechanically coupled to the ultrasonic probe
Display that the ultrasonic transducer is mechanically coupled to the ultrasonic probe
790
END

FIG. 7

ULTRASONIC SURGICAL DEVICE AND METHOD FOR DETECTION OF ATTACHMENT OF ULTRASONIC PROBE

BACKGROUND

Technical Field

The present disclosure relates to an ultrasonic surgical device for verifying integrity of mechanical coupling between an ultrasonic probe and an ultrasonic transducer of the ultrasonic surgical device. More specifically, the present disclosure relates to an ultrasonic surgical device configured to detect attachment of an ultrasonic probe to an ultrasonic transducer.

Background of Related Art

Ultrasonic surgical devices have been demonstrated to provide hemostasis and efficient dissection of tissue with minimum lateral thermal damage and low smoke generation. Unlike electrosurgical devices, which require electrical current to flow through a patient, ultrasonic surgical devices operate by applying mechanical motion through an ultrasonic probe using an ultrasonic transducer that is driven at a resonant frequency. Thus, the ultrasonic surgical devices do not harm tissue due to overexposure of electrical current being passed through the tissue.

However, when the ultrasonic transducer is not mechanically coupled or attached to the ultrasonic probe, the ultrasonic transducer cannot deliver desired mechanical motion so as to obtain desired therapeutic effects. Alternatively, absence of the ultrasonic probe may render the ultrasonic device inoperable as the ultrasonic transducer would be incapable of generating sufficient mechanical motion at the resonant frequency. Thus, there is a need for determining and analyzing the presence or absence of the connection of the ultrasonic probe and the ultrasonic transducer as well as for notifying a clinician of the absence of the ultrasonic probe.

SUMMARY

The present disclosure provides ultrasonic surgical devices, which include an ultrasonic transducer and an ultrasonic probe and are configured to analyze integrity of a mechanical coupling of the ultrasonic probe to the ultrasonic transducer. The present disclosure also provides a method for analyzing the connection between the ultrasonic probe and the ultrasonic transducer.

The ultrasonic surgical device includes a power source configured to generate power, an ultrasonic transducer electrically coupled to the power source and configured to generate ultrasonic motion in response to the generated power, a sensor configured to sense current of the generated power supplied to the ultrasonic transducer, an ultrasonic probe configured to be mechanically couplable to the ultrasonic transducer, and a controller. The controller is configured to receive sensed current from the sensor, perform a frequency response analysis based on the sensed current, calculate a first resonant frequency and a first anti-resonant frequency of the transducer prior to coupling the ultrasonic probe based on the frequency response analysis, calculate a second resonant frequency and a second anti-resonant frequency of the transducer based on the frequency response analysis prior to determining whether the ultrasonic probe is coupled to the ultrasonic transducer, and determine whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second resonant frequencies and the first and second anti-resonant frequencies.

In an aspect, the controller is further configured to calculate a first coupling coefficient based on the first resonant frequency and the first anti-resonance frequencies. The first coupling coefficient is calculated using a formula:

$$k_1^2 = 1 - \frac{f_{r1}^2}{f_{a1}^2},$$

where k_1 is the first coupling coefficient, f_{r1} is the first resonant frequency, and f_{a1} is the first anti-resonant frequency.

In another aspect, the controller is further configured to calculate a second coupling coefficient based on the second resonant frequency and the second anti-resonance frequencies. The second coupling coefficient is calculated using a formula:

$$k_2^2 = 1 - \frac{f_{r2}^2}{f_{a2}^2},$$

where k_2 is the second coupling coefficient, f_{r2} is the second resonant frequency, and f_{a2} is the second anti-resonant frequency.

In another aspect, the controller is further configured to determine whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second coupling coefficients. The controller is further configured to determine whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on a comparison of a difference between the first and second coupling coefficients with a predetermined threshold.

In another aspect, the sensed current has a maximum amplitude response at the first resonant frequency and a minimum amplitude response at the first anti-resonant frequency in response to the ultrasonic probe not being mechanically coupled to the ultrasonic transducer.

In yet another aspect, the sensed current has a maximum amplitude response at the second resonant frequency and a minimum amplitude response at the second anti-resonant frequency in response to the ultrasonic probe being mechanically coupled to the ultrasonic transducer.

The method for detecting a mechanical coupling between an ultrasonic probe and an ultrasonic transducer of an ultrasonic surgical device includes obtaining a first resonant frequency and a first anti-resonant frequency of the ultrasonic transducer without the ultrasonic probe being mechanically coupled to the ultrasonic transducer, detecting a second resonant frequency and a second anti-resonant frequency of the ultrasonic transducer prior to determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer, calculating a first coupling coefficient based on the first resonant frequency and the first anti-resonant frequency, calculating a second coupling coefficient based the second resonant frequency and the second anti-resonant frequency, and determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second coupling coefficients.

In an aspect, obtaining the first resonant frequency and the first anti-resonant frequency includes applying broadband alternating current (AC) signals to the ultrasonic transducer without the ultrasonic probe being mechanically coupled to the ultrasonic transducer, sensing current of the broadband AC signals supplied to the ultrasonic transducer, performing a frequency response analysis of the sensed current, and detecting the first resonant frequency and the first anti-resonant frequency based on the frequency response analysis. The sensed current has a maximum amplitude response at the first resonant frequency and a minimum amplitude response at the first anti-resonant frequency.

In another aspect, detecting a second resonant frequency and a second anti-resonant frequency includes applying broadband alternating current (AC) signals to the ultrasonic transducer prior to determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer, sensing current of the broadband AC signals supplied to the ultrasonic transducer, performing a frequency response analysis of the sensed current, and detecting the second resonant frequency and the second anti-resonant frequency based on the frequency response analysis. The sensed current has a maximum amplitude response at the second resonant frequency and a minimum amplitude response at the second anti-resonant frequency.

In another aspect, the first coupling coefficient is calculated using a formula:

$$k_1^2 = 1 - \frac{f_{r1}^2}{f_{a1}^2},$$

wherein k_1 is the first coupling coefficient, f_{r1} is the first resonant frequency, and f_{a1} is the first anti-resonant frequency.

In another aspect, the second coupling coefficient is calculated using a formula:

$$k_2^2 = 1 - \frac{f_{r2}^2}{f_{a2}^2},$$

where k_2 is the second coupling coefficient, f_{r2} is the second resonant frequency, and f_{a2} is the second anti-resonant frequency.

In yet another aspect, determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer further includes comparing a difference between the first and second coupling coefficients with a predetermined threshold.

In an aspect, the method further includes displaying a message in response to the determination of whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer.

In another aspect, the method further includes generating an optical or audible signal in response to the determination of whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure may be understood by reference to the accompanying drawings, when considered in conjunction with the subsequent, detailed description, in which:

FIG. **1**A is a side elevation view of an ultrasonic surgical device in accordance with embodiments of the present disclosure;

FIG. **1**B is a perspective view of parts separated, which shows the left side of a handle, an ultrasonic transducer, and a right side of the handle of the ultrasonic surgical device of FIG. **1**A in accordance with embodiments of the present disclosure;

FIG. **2** is a side cross-sectional elevation view of an ultrasonic surgical pen in accordance with embodiments of the present disclosure;

FIG. **3** is a block diagram of the ultrasonic surgical device of FIG. **1**A in accordance with embodiments of the present disclosure;

FIG. **4** is a circuit diagram illustrating a circuit model of an ultrasonic transducer or an ultrasonic transducer connected to the probe of the ultrasonic surgical device of FIG. **1**A in accordance with embodiments of the present disclosure;

FIG. **5** is a graphical illustration of frequency responses of current flowing through an ultrasonic transducer in accordance with embodiments of the present disclosure;

FIG. **6** is a block diagram illustrating coupling between the ultrasonic transducer and the ultrasonic probe of the ultrasonic surgical device of FIG. **1**A in accordance with embodiments of the present disclosure; and

FIG. **7** is a flow chart of a method for analyzing the connection between the ultrasonic transducer and the ultrasonic probe in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION

Generally, the present disclosure provides an ultrasonic surgical device for detecting a defect in a connection between an ultrasonic transducer and an ultrasonic probe of an ultrasonic surgical device. The ultrasonic transducer is configured to generate ultrasonic mechanical motion at its resonant frequency. The ultrasonic surgical device also includes a processor that is programmed to detect a mechanical coupling between the ultrasonic transducer and the ultrasonic probe based on the changes in the resonant frequency of the ultrasonic transducer.

A pulse-width modulation (PWM) amplitude control is employed to regulate the mechanical motion of the ultrasonic probe and to provide different levels of power for treating tissue. Further, a proportional-integral (PI) controller is included to obtain a rapid transient response to changes in load and to maintain stable surgical operations.

The ultrasonic surgical device also includes two control loops, which may be embodied in hardware and/or software executed by the processor, to control the ultrasonic mechanical motion of the ultrasonic transducer, which is energized by a DC power source. The first loop is an amplitude control loop configured to regulate the longitudinal mode displacement and includes a closed-loop feedback control. The second loop generates an AC signal from the DC power supplied to the ultrasonic transducer and automatically tracks the resonant frequency of the ultrasonic transducer. The second control loop includes a band-pass filter oscillator. By using the first and second control loops, the ultrasonic surgical device provides regulated ultrasonic mechanical motion at resonant frequency sufficient to treat tissue in accordance with embodiments of this disclosure.

With reference to FIGS. **1**A-**1**B, an ultrasonic surgical device **100** for treating tissue is illustrated. The ultrasonic surgical device **100** includes a power source **110**, a housing **130**, an ultrasonic transducer **150**, and an ultrasonic probe **190**. The power source **110** provides DC power to the ultrasonic transducer **150**. In an aspect, the power source **110** may be a battery that directly provides DC power. In a further aspect, the power source **110** may be insertable or integrated into the housing **130** so that the ultrasonic surgical device **100** may be portably carried without disturbances of any cable. In yet another aspect, the power source **110** may be rechargeable so that the power source **110** may be reusable.

In another aspect, the power source **110** may include a converter that is connected to an alternating current (AC) power source and converts the AC power to DC power. The AC power source may be of a relatively low frequency, such as about 60 hertz (Hz), while the ultrasonic surgical device **100** may operate at a higher frequency, such as 55.5 kilo hertz (kHz). Thus, the power source **110** may convert the low frequency AC power to DC power so that the DC power may then be inverted to AC power having a frequency suitable to cause the ultrasonic transducer **150** to generate ultrasonic mechanical motion.

With continued reference to FIGS. **1**A and **1**B, the housing **130** includes a handle portion **131** having a compartment **132**, which houses the power source **110**, and a power source door **134** that secures the power source **110** within the compartment **132**. In an aspect, the power source door **134** may be configured to form a water-tight seal between the interior and the exterior of the compartment **132**.

The housing **130** also includes a cover **133**, which houses the ultrasonic transducer **150** and an output device **180**. The ultrasonic transducer **150** includes a generator assembly **152** and a transducer assembly **154**, having a transducer body **156** and a locking portion **162**. The generator assembly **152** is electrically coupled to the transducer assembly **154** via a pair of contacts **158**.

With reference to FIG. **1**B, the ultrasonic transducer **150** is illustrated as being separate from the cover **133**. When the ultrasonic transducer **150** is inserted into and assembled with the cover **133**, the pair of contacts **158** is connected to the round groove of the ultrasonic transducer **150** so that the rotational movement of the transducer body **156** does not disrupt the connection between the transducer body **156** and the generator assembly **152**. Thus, the transducer body **156** is capable of freely rotating within the housing **130**.

The output device **180** outputs information about the ultrasonic surgical device **100** or a status of the mechanical coupling between the ultrasonic probe **190** and the ultrasonic transducer **150**. The output device **180** may also display a warning that the ultrasonic probe **190** is not mechanically coupled to the ultrasonic transducer **150**.

In another aspect, the output device **180** may be a speaker configured to output audible tones denoting no connection between the ultrasonic probe **190** and the ultrasonic transducer **150**. In yet another aspect, the output device **180** may include one or more light emitting devices, configured to emit lights of various duration, pulses, and colors indicating the status of the mechanical coupling between the ultrasonic probe **190** and the ultrasonic transducer **150**.

The handle portion **131** further includes a trigger **136**. When the trigger **136** is actuated, the power source **110** provides energy to the ultrasonic transducer **150** so that the ultrasonic transducer **150** is powered to generate ultrasonic mechanical motion of the ultrasonic probe **190**. As the trigger **136** is released, the power supply to the ultrasonic transducer **150** is terminated.

The generator assembly **152** receives the DC power from the power source **110** and generates AC signals having an ultrasonic frequency. The generator assembly **152** may be capable of generating signals having a frequency based on a desired mode of operation, which may be different from the resonant frequency of the ultrasonic transducer **150**.

In an aspect, the generator assembly **152** may generate AC signals having a relatively wide range of frequencies (e.g., broadband signals) or a relatively small range of frequencies (e.g., narrowband signals). The broadband AC signals may be used to detect a resonant frequency and an anti-resonant frequency of the ultrasonic transducer **150**. Presence or absence of the connection between the ultrasonic probe **190** and the ultrasonic transducer **150** may be analyzed based on the resonant and anti-resonant frequencies as described in further detail below.

The transducer body **156** of the transducer assembly **154** receives the AC signal generated by the generator assembly **152** and generates ultrasonic mechanical motion within the ultrasonic probe **190** based on the amplitude and the frequency of the generated AC signal. The transducer body **156** includes a piezoelectric material, which converts the generated AC signal into ultrasonic mechanical motion. The transducer body **156** may be based on an electrical oscillator model having an inductor and a capacitor, which oscillates between charging and discharging electrical energy. This oscillation model for the transducer body **156** is described further in detail below with respect to FIG. **4**.

The ultrasonic surgical device **100** also includes a spindle **170**, which is coupled to the ultrasonic probe **190** and allows for rotation of the ultrasonic probe **190** about its longitudinal axis. The ultrasonic probe **190** is attached to the housing and is mechanically coupled to the ultrasonic transducer **150** via the locking portion **162** such that as the spindle **170** is rotated about the longitudinal axis defined by the ultrasonic probe **190**, the ultrasonic probe **190** and the ultrasonic transducer **150** are also rotated correspondingly without affecting the connection between the ultrasonic transducer **150** and the ultrasonic probe **190**. Additionally, as the spindle **170** is rotated, the ultrasonic transducer **150** may be also rotated along with the ultrasonic probe **190**.

FIG. **1**B illustrates the ultrasonic transducer **150** separated from the handle portion **131** of the housing **130** of FIG. **1**A. The ultrasonic transducer **150** includes a slidable first connector **164** and the handle portion **131** of the housing **130** includes a second connector **142** configured and dimensioned to engage the slidable first connector **164** allowing for selective engagement of the ultrasonic transducer **150** with the handle portion **131**.

The locking portion **162** physically and/or mechanically locks the ultrasonic probe **190** to the ultrasonic transducer **150**. The locking portion **162** maintains physical contact between the ultrasonic probe **190** and the transducer body **156** as the ultrasonic probe **190** is rotated. The locking portion **162** conveys the ultrasonic mechanical motion from the transducer body **156** to the ultrasonic probe **190** without losing the connection. In an aspect, the locking portion **162** may be a male connector and the ultrasonic probe **190** may include a counterpart female connector.

The ultrasonic probe **190** may include an end effector suitable for sealing tissue. The ultrasonic probe **190** includes a waveguide **192**, a blade **194** extending from the waveguide **192**, and a jaw member **196**. The ultrasonic probe **190** is mechanically coupled to the transducer body **156** via the locking portion **162**.

The jaw member **196** may be formed as a pivoting arm configured to grasp and/or clamp tissue between the jaw member **196** and the blade **194**. When the jaw member **196** and the blade **194** grasp tissue and the blade **194** conveys the ultrasonic mechanical motion, temperature of the grasped tissue between the blade **194** and the jaw member **196** increases due to the ultrasonic mechanical motion. This motion in turn treats, e.g., cuts and/or seals, tissue.

In instances when the ultrasonic probe **190** is not attached to the ultrasonic transducer **150**, the ultrasonic mechanical motion generated by the ultrasonic transducer **150** cannot be delivered to the ultrasonic probe **190**. As a result, the ultrasonic surgical device **100** cannot be used to treat the tissue. The ultrasonic surgical device **100** according to the present disclosure is configured to determine whether or not the ultrasonic probe **190** is mechanically coupled to the ultrasonic transducer **150** to ensure operations of the ultrasonic probe **190**.

FIG. **2** shows an ultrasonic surgical pen **200**, which is another illustrative embodiment of the ultrasonic surgical device **100** of FIG. **1**A. The ultrasonic surgical pen **200** includes a power source **210**, the housing **230**, the ultrasonic transducer **250**, and the ultrasonic probe **290**. The power source **210**, the housing **230**, and the ultrasonic transducer **250** of the ultrasonic surgical pen **200** are substantially similar to the power source **110**, the housing **130**, and the ultrasonic transducer **150** of the ultrasonic surgical device **100**, respectively. The ultrasonic probe **290** may be an ultrasonic cauterizer. The shape and dimensions of the housing **230** of the ultrasonic surgical pen **200** also provide for a different ergonomic option than the ultrasonic surgical device **100**.

FIG. **3** illustrates a block diagram of the ultrasonic surgical device **100** using a band-pass filter (BPF) oscillator architecture, which tracks the resonant frequency of the BPF regardless of process variations and environmental interferences. A pulse-width modulation (PWM) signal is used to regulate ultrasonic mechanical motion as described in further detail below.

The ultrasonic surgical device **100** includes the power source **110**, an amplitude controller **320**, and a resonance tracking controller **360**. The amplitude controller **320** includes a converter **330**, a sensor **340** and a controller **350**. The resonance tracking controller **360** includes a non-resonant inverter **370**, the ultrasonic transducer **150**, and a comparator **390**.

The power source **110** provides DC power to the amplitude controller **320**, which controls amplitude of the output of the amplitude controller **320** so that ultrasonic surgical device **100** generates ultrasonic mechanical motion suitable for treating tissue. In an aspect, when the DC power is provided, the converter **330** amplifies the amplitude of the DC power. The converter **330** may be a buck converter or a step-down converter. The sensor **340** then senses current flowing to the resonance tracking controller **360**. The controller **350** receives the sensed results from the sensor **340** and generates a digital pulse width modulated (PWM) control signal to control a duty cycle of the converter **330**.

The resonant tracking controller **360** is configured to generate ultrasonic motion at a frequency substantially equal to the resonant frequency of the ultrasonic transducer **150**. In an aspect, the non-resonant inverter **370** receives the amplified DC power from the converter **330** and inverts to AC power having a first frequency. The non-resonant inverter **370** is driven by output signals from the comparator **390**. The comparator **390** adjusts the frequency of the AC power from an initial (e.g., first) frequency until the frequency is substantially equal to the resonant frequency of the ultrasonic transducer **150**. The non-resonant inverter **370** may include any suitable electrical topology such as an H-bridge (e.g., full bridge), a half bridge, and the like.

In an aspect, the output signals from the comparator **390** may be digitally generated by the controller **350**. The controller **350** may be a programmable gate array (PGA), field-programmable gate array (FPGA), application-specific integrated circuit (ASIC), complex programmable logic device (CPLD), or any other suitable logic device.

The controller **350** also generates PWM control signals to drive the converter **330** and resonant control signals for the non-resonant inverter **370**. The controller **350** receives outputs from the comparator **390** and generates resonant signals for the non-resonant inverter **370** in response to the output of the comparator **390**. The non-resonant inverter **370** then inverts the DC power to the AC signal, whose frequency is independent of the switching frequency of the non-resonant inverter **370**, by tracking the resonant frequency of the ultrasonic transducer **150**.

In an aspect, a transformer (not shown) may be electrically coupled between the non-resonant inverter **370** and the ultrasonic transducer **150** so that the transformer may increase or decrease the amplitude of the inverted AC power to a desired level.

The ultrasonic transducer **150** receives the AC power having a first frequency and generates ultrasonic mechanical motion. In a case when the frequency of the AC signals is different from the resonant frequency of the ultrasonic transducer **150**, ultrasonic mechanical motion generated by the ultrasonic transducer **150** may not be optimal for intended purposes. The comparator **390** is configured to track the resonant frequency of the ultrasonic transducer **150** to cause the frequency of the AC signal to match the resonant frequency of the ultrasonic transducer **150** to provide for optimal operation of the ultrasonic transducer **150**.

In an aspect, the resonance tracking controller **360** may include a resonant inverter (not shown) connected to the ultrasonic transducer **150** without the non-resonant inverter **370** and the comparator **390**. The resonant inverter may be configured to invert the amplified DC signals and generate AC signal having a frequency substantially equal to the resonant frequency of the ultrasonic transducer **150**.

In an aspect, the resonant tracking controller **360** may be used to detect a resonant frequency of the ultrasonic transducer **150**. The sensor **340** is configured to sense voltage and current of the broadband AC signals applied to the ultrasonic transducer **150** and transmit the sensor signals to the controller **350**. The controller **350** digitally processes the sensor signals and monitors the voltage and current values. Further, the controller **350** performs frequency response analysis (e.g., Fourier transformation, digital Fourier transformation, or other frequency related analysis) to identify amplitude response with respect to frequencies of the current. The resonant frequency of the ultrasonic transducer **150** may be a frequency at which the amplitude response of the current is the maximum and the anti-resonant frequency of the ultrasonic transducer **150** may be a frequency at which the amplitude response of the current is the minimum.

FIG. **4** shows electrical circuit models **400** and **450** of the ultrasonic transducer **150** of FIG. **1**A in accordance with embodiments of the present disclosure. The electrical circuit model **400** or **450** model resonant or anti-resonant behavior of the ultrasonic transducer **150**. The electrical circuit model **400** is a series resistor-inductor-capacitor (RLC) circuit including a resistor **410**, a capacitor **420**, and an inductor **430**, which is connected in parallel with another capacity **440**.

The resonant frequency f_r of the circuit **400** is calculated using formula (I) below:

$$f_r = \frac{1}{2\pi\sqrt{L_1 \cdot C_1}}, \tag{I}$$

where L_1 is the inductance of the inductor **430** and C_1 is the capacitance of the capacitor **420**. Based on the circuit **400**, the inductance and the capacitance of the ultrasonic transducer **150** determines the resonant frequency of the ultrasonic transducer **150**.

The ultrasonic transducer **150** converts electrical energy into mechanical motion fully at the resonant frequency of the ultrasonic transducer **150**. In other words, when the ultrasonic transducer **150** is operated at a frequency different from the resonant frequency, the ultrasonic transducer **150** does not operate optimally. Further, when the ultrasonic probe **190** is not mechanically coupled to the ultrasonic transducer **150**, the ultrasonic probe **190** cannot deliver the ultrasonic motion to tissue for intended therapeutic purposes and the ultrasonic transducer **150** may maintain its resonant frequency and anti-resonant frequency.

In an aspect, the resonant frequency of the ultrasonic transducer **150** or the ultrasonic probe **190** may be obtained by testing and/or during manufacturing. In another aspect, the resonant frequencies may be measured and calculated or identified by the controller **350** of the ultrasonic surgical device **100**. Determination of the resonant frequency may be accomplished using the comparator **390** with the non-resonant inverter **370**, which can track the resonant frequency. The non-resonant inverter **370** may apply AC signals at a single frequency to the ultrasonic transducer **150** for a predetermined time and the comparator **390** may then track the frequency of the electrical energy until the resonant frequency is identified. The resonant frequency of the ultrasonic probe **190** may also be identified or measured using other techniques known in the related art.

In another aspect, when a broadband frequency AC signal is provided to the ultrasonic transducer **150**, the controller **350** performs frequency response analysis and identifies the resonant frequency at which the frequency response is the maximum and the anti-resonant frequency at which the frequency response is the minimum.

When a voltage source is connected to the circuit **400**, due to the potential difference, a current flows through the circuit **400**. Then, the anti-resonant frequency f_a of the **400** is calculated by:

$$f_a = \frac{1}{2\pi\sqrt{L_1 \cdot \left(\frac{C_1 \cdot C}{C_1 + C}\right)}}. \tag{II}$$

This frequency f_a is an anti-resonant frequency because the frequency response is the minimum at the anti-resonant frequency f_a, when the electrical impedance of the ultrasonic transducer **150** is the maximum.

FIG. **5** shows a frequency response graph **500** illustrating amplitude responses of current in frequency domain, which flows through the ultrasonic surgical device **100** in accordance with embodiments of the present disclosure. FIG. **5** also illustrates frequency responses at the resonant frequency f_r and the anti-resonant frequency f_a. The vertical axis **510** of the frequency response graph **500** represents amplitudes of current passing through an ultrasonic transducer **150** of the ultrasonic surgical device **100** and the horizontal axis **520** of the frequency response graph **500** represents frequencies of the current. When broadband AC signals are applied to the ultrasonic transducer **150**, a frequency response curve **530** may be obtained by the controller **350** of the ultrasonic surgical device **100**. As shown in the frequency response curve **530**, the amplitude of the current has the maximum value at a first frequency **540** and the minimum value at a second frequency **550**. The first frequency **540** corresponds to the resonant frequency f_r of the ultrasonic transducer **150** and the second frequency **550** corresponds to the anti-resonant frequency f_a of the ultrasonic transducer **150**.

The ultrasonic transducer **150** by itself or a combined body of the ultrasonic transducer **150** and the ultrasonic probe **190** exhibit different resonant and the anti-resonance frequencies. Thus, presence or absence of the ultrasonic probe **190** can be detected based on the resonant and anti-resonance frequencies. This will be further described below with respect to FIG. **7**.

FIG. **6** shows a block diagram **600** illustrating a connected state of the ultrasonic transducer **150** and the ultrasonic probe **190**. The resonant and anti-resonant frequencies of the connected body **610** depend upon mechanical coupling between the ultrasonic probe **190** and the ultrasonic transducer **150**. When the ultrasonic probe **190** is not mechanically coupled to the ultrasonic transducer **150**, the connected body **610** may have resonant and anti-resonant frequencies similar to those of the ultrasonic transducer **150** not being coupled to the ultrasonic probe **190**. When the ultrasonic probe **190** is mechanically coupled to the ultrasonic transducer **150**, the connected body **610** will have resonant and/or anti-resonant frequencies different to those of the ultrasonic transducer **150**.

The present disclosure utilizes coupling coefficients, which may be used to determine mechanical coupling between the ultrasonic transducer **150** and the ultrasonic probe **190**. A first coupling coefficient k_1 is representative of the ultrasonic probe **190** being absent from the ultrasonic surgical device **100** or not being mechanically coupled to the ultrasonic transducer **150**. The first coupling coefficient k_1 is calculated by:

$$k_1^2 = 1 - \frac{f_{r1}^2}{f_{a1}^2}, \tag{III}$$

where f_{r1} is the resonant frequency and f_{a1} is the anti-resonant frequency of the ultrasonic transducer **150**.

A second coupling coefficient k_2 is representative of the ultrasonic probe **190** being present in the ultrasonic surgical device **100** or being mechanically coupled to the ultrasonic transducer **150**. In the same way, second coupling coefficient k_2 is calculated by:

$$k_2^2 = 1 - \frac{f_{r2}^2}{f_{a2}^2}, \tag{IV}$$

where f_{r2} is the resonant frequency and f_{a2} is the anti-resonant frequency of the combined body **610**.

When the second coupling coefficient k_2 differs significantly from the first coupling coefficient k_1, the ultrasonic probe **190** is determined to be present in the ultrasonic surgical device **100** or mechanically coupled to the ultrasonic transducer **150**. After it is determined that the ultrasonic probe **190** is mechanically coupled to the ultrasonic transducer **150**, it may be further determined whether or not the ultrasonic probe **190** is properly mechanically coupled to the ultrasonic transducer **150**. Details of this determination may be found in a commonly assigned U.S. patent application Ser. No. entitled "Ultrasonic Surgical Device and Method For Detection of Attachment of Ultrasonic Probe," the entire contents of which are incorporated by reference herein. Conversely, when the second coupling coefficient k_2 is substantially the same as the first coupling coefficient k_1, the ultrasonic probe **190** is absent in the ultrasonic surgical device **100**.

FIG. **7** shows a method **700** for determining presence or absence of the ultrasonic probe **190** in the ultrasonic surgical device **100** in accordance with embodiments of the present disclosure. At step **710**, a first resonant frequency and a first anti-resonant frequency of the ultrasonic transducer **150** are obtained, when the ultrasonic probe **190** is not coupled to the ultrasonic transducer **150**. The first resonant and anti-resonant frequencies of the ultrasonic transducer **150** may be obtained in a manner described above.

In an aspect, first resonant and anti-resonant frequencies may be obtained from applying broadband AC signals to the ultrasonic transducer **150**. A sensor of the ultrasonic surgical device **100** senses the broadband AC signals passing through the ultrasonic transducer **150** and transmits to a controller **350**. The sensed results may be digitally sampled and then transmitted to the controller **350**, which then performs frequency response analysis on the sensed results. The controller **350** may set a frequency, at which the amplitude response of the current is the maximum, as the first resonant frequency and set a frequency, at which the amplitude of the current is the minimum, as the first anti-resonant frequency.

In step **720**, the controller **350** may calculate the first coupling coefficient k_1 using the formula (III) above. In step **730**, before it is determined or when it is unknown whether or not the ultrasonic probe **190** is mechanically coupled to the ultrasonic transducer **150**, the broadband AC signals are applied to the ultrasonic transducer **150**. As noted above, the bandwidth of the broadband AC signals has a wide range of frequencies sufficient to include the first resonant and first anti-resonant frequencies.

In step **735**, the sensor **340** senses the voltage and current of the applied broadband AC signals and transmits the measurements to the controller **350**. As described above, the sensed results may be digitally sampled. The controller **350** performs frequency response analysis on the sensed results in step **740**.

In step **745**, the controller **350** calculates a second resonant frequency as a frequency at which the amplitude of the current is at its maximum based on the frequency response analysis and calculates a second anti-resonant frequency as a frequency at which the amplitude response of the current is at its the minimum.

In step **750**, the controller **350** may calculate the second coupling coefficient k_2 using the formula (IV) above. The controller **350** also calculates a difference between the first and second coupling coefficients in step **760**. The difference is compared with a predetermined threshold in step **770** to determine if there is a substantial difference between coupling coefficients, which is indicative of the ultrasonic probe **190** being attached to the ultrasonic transducer **150**. When it is determined that the difference is less than the predetermined threshold, in step **780**, a message is displayed to indicate that the ultrasonic probe **190** is absent in the ultrasonic surgical device **100** or is not mechanically coupled to the ultrasonic transducer **150**.

When it is determined that the difference is greater than or equal to the predetermined threshold in step **770**, in step **790**, a message is displayed to indicate that the ultrasonic probe **190** is present in the ultrasonic surgical device **100** or is mechanically coupled to the ultrasonic transducer **150**. By displaying a message in step **780** or **790**, the method **700** for determining presence or absence of the ultrasonic probe **190** is ended.

In an aspect, when the message indicates that the ultrasonic probe **190** is absent in the ultrasonic surgical device **100** or is not mechanically coupled to the ultrasonic transducer **150** in step **780**, a clinician using the ultrasonic surgical device **100** may connect the ultrasonic probe **190** with the ultrasonic transducer **150** so that the clinician can use the ultrasonic surgical device **100** to perform operations.

Since other modifications and changes may be made to fit particular operating requirements and environments, it is to be understood by one skilled in the art that the present disclosure is not limited to the illustrative examples described herein and may cover various other changes and modifications which do not depart from the spirit or scope of this disclosure.

What is claimed is:

1. An ultrasonic surgical device comprising:
a power source configured to generate power;
an ultrasonic transducer electrically coupled to the power source and configured to generate ultrasonic motion in response to the generated power;
a sensor configured to sense current of the generated power supplied to the ultrasonic transducer;
an ultrasonic probe configured to be mechanically couplable to the ultrasonic transducer; and
a controller configured to:
  receive sensed current from the sensor;
  perform a frequency response analysis based on the sensed current;
  calculate a first resonant frequency and a first anti-resonant frequency of the ultrasonic transducer prior to coupling the ultrasonic probe based on the frequency response analysis;
  calculate a second resonant frequency and a second anti-resonant frequency of the ultrasonic transducer based on the frequency response analysis prior to determining whether the ultrasonic probe is coupled to the ultrasonic transducer; and
  determine whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second resonant frequencies and the first and second anti-resonant frequencies.

2. The ultrasonic surgical device according to claim **1**, wherein the controller is configured to calculate a first coupling coefficient based on the first resonant frequency and the first anti-resonance frequencies.

3. The ultrasonic surgical device according to claim **2**, wherein the first coupling coefficient is calculated using a formula:

$$k_1^2 = 1 - \frac{f_{r1}^2}{f_{a1}^2},$$

where k_1 is the first coupling coefficient, f_{r1} is the first resonant frequency, and f_{a1} is the first anti-resonant frequency.

4. The ultrasonic surgical device according to claim **3**, wherein the controller is configured to calculate a second coupling coefficient based on the second resonant frequency and the second anti-resonance frequencies.

5. The ultrasonic surgical device according to claim **4**, wherein the second coupling coefficient is calculated using a formula:

$$k_2^2 = 1 - \frac{f_{r2}^2}{f_{a2}^2},$$

where k_2 is the second coupling coefficient, f_{r2} is the second resonant frequency, and f_{a2} is the second anti-resonant frequency.

6. The ultrasonic surgical device according to claim **5**, wherein the controller is configured to determine whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second coupling coefficients.

7. The ultrasonic surgical device according to claim **6**, wherein the controller is configured to determine whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on a comparison of a difference between the first and second coupling coefficients with a predetermined threshold.

8. The ultrasonic surgical device according to claim **1**, wherein the sensed current has a maximum amplitude response at the first resonant frequency and a minimum amplitude response at the first anti-resonant frequency in response to the ultrasonic probe not being mechanically coupled to the ultrasonic transducer.

9. The ultrasonic surgical device according to claim **1**, wherein the sensed current has a maximum amplitude response at the second resonant frequency and a minimum amplitude response at the second anti-resonant frequency in response to the ultrasonic probe being mechanically coupled to the ultrasonic transducer.

10. A method for detecting a mechanical coupling between an ultrasonic probe and an ultrasonic transducer of an ultrasonic surgical device, the method comprising:

applying alternating current (AC) signals to the ultrasonic transducer without the ultrasonic probe being mechanically coupled to the ultrasonic transducer;

sensing current of the AC signals supplied to the ultrasonic transducer;

performing a frequency response analysis based on the sensed current:

calculating a first resonant frequency and a first anti-resonant frequency of the ultrasonic transducer without the ultrasonic probe being mechanically coupled to the ultrasonic transducer based on the frequency response analysis;

calculating a second resonant frequency and a second anti-resonant frequency of the ultrasonic transducer based on the frequency response analysis prior to determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer;

calculating a first coupling coefficient based on the first resonant frequency and the first anti-resonant frequency;

calculating a second coupling coefficient based the second resonant frequency and the second anti-resonant frequency; and

determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer based on the first and second coupling coefficients.

11. The method according to claim **10**, wherein the AC signal is a broadband AC signal.

12. The method according to claim **10**, wherein the sensed current has a maximum amplitude response at the first resonant frequency and a minimum amplitude response at the first anti-resonant frequency.

13. The method according to claim **10**, wherein detecting a second resonant frequency and a second anti-resonant frequency includes:

applying broadband alternating current (AC) signals to the ultrasonic transducer prior to determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer;

sensing current of the broadband AC signals supplied to the ultrasonic transducer;

performing a frequency response analysis of the sensed current; and

detecting the second resonant frequency and the second anti-resonant frequency based on the frequency response analysis.

14. The method according to claim **13**, wherein the sensed current has a maximum amplitude response at the second resonant frequency and a minimum amplitude response at the second anti-resonant frequency.

15. The method according to claim **10**, wherein the first coupling coefficient is calculated using a formula:

$$k_1^2 = 1 - \frac{f_{r1}^2}{f_{a1}^2},$$

wherein k_1 is the first coupling coefficient, f_{r1} is the first resonant frequency, and f_{a1} is the first anti-resonant frequency.

16. The method according to claim **10**, wherein the second coupling coefficient is calculated using a formula:

$$k_2^2 = 1 - \frac{f_{r2}^2}{f_{a2}^2},$$

where k_2 is the first coupling coefficient, f_{r2} is the second resonant frequency, and f_{a2} is the second anti-resonant frequency.

17. The method according to claim **10**, wherein determining whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer further includes comparing a difference between the first and second coupling coefficients with a predetermined threshold.

18. The method according to claim **10**, further comprising displaying a message in response to the determination of whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer.

19. The method according to claim **10**, further comprising generating an optical or audible signal in response to the determination of whether the ultrasonic probe is mechanically coupled to the ultrasonic transducer.

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